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Quantitative Comparison of Four Brain Extraction Algorithms

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ABSTRACT

Segmentation of brain/non-brain tissue is one of the most time-consuming preprocessing steps performed in neuroimaging laboratories, and numerous brain extraction algorithms (BEAs) have been developed to perform this step automatically. While BEAs speed up overall image processing, their output quality varies greatly and can affect the results of subsequent image analysis. We therefore compared the performance of four BEAs against manual brain extraction using a high-resolution set of T1-weighted MRI brain volumes.

INTRODUCTION

Four algorithms for brain/non-brain segmentation were evaluated:

- Statistical Parametric Mapping (SPM), v. 2b [1]
- Brain Extraction Tool (BET), v. 1.2 [2]
- Minneapolis Consensus Strip (McStrip) [3]
- Brain Surface Extractor (BSE), v. 2.99.8 [4]

Each of these BEAs employs a different approach to brain/non-brain segmentation.

SPM

Although SPM does not explicitly create a brain mask, one can be created as the sum of the grey matter (GM) and white matter (WM) compartments [5]. See Fig. 1.

BET

BET makes an intensity-based estimation of the brain/non-brain threshold, determines the center of gravity of the head, defines a starting sphere based on the center of gravity, and deforms the tessellated sphere outward toward the brain surface [2]. See Fig. 2.

Figure 1.
Output from the *Segment* routine in SPM2b. Columns left to right: T1 MRI volume, GM, WM.

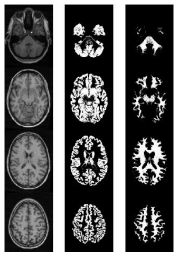
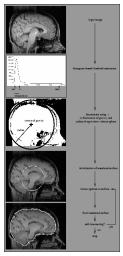


Figure 2.
BET processing stages [6].



McStrip

McStrip is initialized with a warp mask using AIR [7], and dilates the AIR mask to form a Coarse Mask. It then estimates a brain/non-brain threshold based on the intensity histogram, and automatically adjusts this threshold to produce a Threshold Mask. The volume of tissue within the Threshold Mask determines the choice of the BSE Mask from among a suite of 15 masks computed using parameter combinations spanning both smoothing and edge parameters. The final, McStrip Mask is a union of the Threshold and BSE masks after void filling and smoothing. See Figs. 3 and 4.

Figure 3
McStrip processing stages.

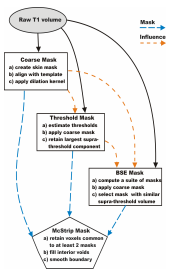
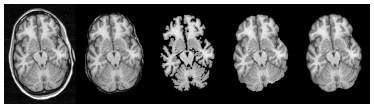


Figure 4.
McStrip processing (from left to right): raw volume, Coarse Mask, Threshold Mask, BSE Mask, McStrip Mask.



BSE

BSE is an edge-based method that employs anisotropic diffusion filtering. Edge detection is implemented using a 2D Marr-Hildreth operator, employing low-pass filtering with a Gaussian kernel and localization of zero crossings in the Laplacian of the filtered image. The final step is morphological processing of the edge map [8].

METHODS

Sixteen T1-weighted MRI scans of normal subjects were acquired during a fMRI static force experiment [9]. Voxel dimensions were 0.86 x 0.86 x 1 mm. Manual brain extraction was performed by two of the authors (KR and SS). Manual masks were used as the *gold standard* against which the performance of the BEAs was compared.

SPM

SPM2b *Realign* and *Normalize* routines were used to prepare files for input into the *Segment* routine, which generated grey- and white-matter volumes. The final mask was the binarized sum of the grey- and white-matter volumes.

BET

Two initial parameters are user adjustable: Fractional Intensity Threshold (FIT, default 0.50) and Threshold Gradient (TG, default 0.0). These parameters were tuned on two training volumes, and those which resulted in the *best* strip (removal of scalp, skull, CSF and dura with preservation of brain tissue) were applied to all 16 brain volumes (FIT = 0.45, TG = 0.0).

McStrip

Parameter settings were as follows: warp mask, third-order polynomial; dilation kernel, 7x7x7 voxels; grey threshold, 15-35%; smoothing kernel FWHM, 3mm. BSE parameters were: anisotropic smoothing kernels: 5, 10, 15; iterations, 3; edge detection σ's: 0.60, 0.64, 0.70, 0.80, 0.90.

BSE

Subject-specific Parameters

The BSE mask generated by McStrip was used in our comparisons.

Fixed Parameters

Three initial parameters are user adjustable: anisotropic smoothing kernel (ASK, default = 5), iterations (ITER, default = 3), edge detection σ (default = 0.75). Initial parameters were tuned on two training volumes, and the parameter set resulting in the *best* strip was employed for all 16 subjects: ASK = 0, ITER = 0, σ = 0.90.

PERFORMANCE METRICS

The following performance metrics were calculated:

- *Processing Time*
- *Correct Boundary*: the percentage of the manual mask boundary with a corresponding BEA boundary (within 1 voxel). See Fig. 5.
- *Pertinent Boundary*: the *Correct Boundary* plus those segments where differences in the BEA and manual boundaries do not involve high-intensity voxels (those voxels with values greater than the grey matter-CSF threshold). See Fig. 6.
- *Misclassified Brain Tissue*: the percentage of high-intensity brain tissue incorrectly included in or excluded from the BEA mask relative to the manual mask.

Figure 5. Left, Manual brain outline (green); **Center**, BEA outline (red); **Right**, red indicates *significant* mismatch between outlines, green indicates correct boundary.

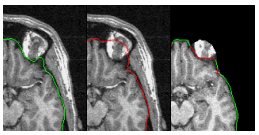
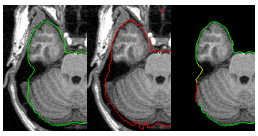


Figure 6. Left, Manual brain outline (green); **Center**, BEA outline (red); **Right**, red indicates *significant* mismatch between outlines, green indicates correct boundary, yellow indicates boundary segment that did not involve high-intensity voxels.



RESULTS

One volume that could not be satisfactorily stripped by any of the BEAs was excluded from the averages reported in Tables 1 and 2.

Table 1. BEA performance vs. KR's manual mask.

BEA	Processing Time	Correct Boundary	Pertinent Boundary	Misclassified Tissue
SPM	50 min	60.2%	64.4%	3.7%
BET	40 sec	66.1%	69.1%	11.4%
McStrip	75 min	86.8%	87.9%	2.0%
BSE, Subject-Specific	3-15 min	35.5%	43.6%	4.6%
BSE, Fixed	1 min	30.9%	42.2%	20.5%

The best performance for each metric is colored green.

RESULTS

Table 2. BEA performance vs. SS's manual mask.

BEA	Processing Time	Correct Boundary	Pertinent Boundary	Misclassified Tissue
SPM	50 min	42.9%	47.9%	4.0%
BET	40 sec	46.9%	53.7%	10.9%
McStrip	75 min	65.7%	72.7%	2.4%
BSE, Subject-Specific	3-15 min	18.7%	24.3%	5.2%
BSE, Fixed	1 min	17.1%	21.9%	20.2%

The best performance for each metric is colored green.

Figures 7 and 8 demonstrate characteristic results for each of the BEAs. The subject shown in Figure 8 was one of the two training volumes used for BET and BSE (fixed parameters).

Figure 7. Axial brain slices from Subject 1 extracted by hand and by BEAs. **Columns from left to right:** raw volume, manual extraction (KR), SPM, BET, McStrip, BSE (subject-specific parameters), BSE (fixed parameters).

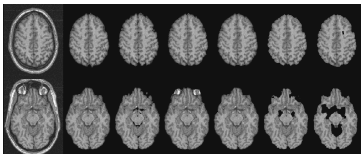
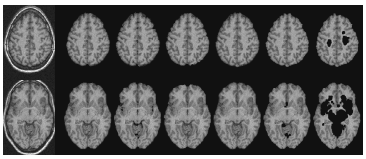


Figure 8. Axial brain slices from Subject 2 extracted by hand and by BEAs. **Columns from left to right:** raw volume, manual extraction (KR), SPM, BET, McStrip, BSE (subject-specific parameters), BSE (fixed parameters).



CONCLUSIONS

BET and BSE were significantly faster than SPM or McStrip. When compared against two different manual strip-masks, McStrip outperformed BET, SPM and BSE based on the *Correct Boundary* and *Pertinent Boundary* criteria and misclassified the least number of brain voxels; SPM and BSE (using subject-specific parameters) performed nearly as well with regard to misclassified voxels. BSE performed significantly better with subject-specific parameters than with fixed parameters.

We are in the process of creating a Web service that will download our unstripped dataset (15 T1-weighted MRI brain volumes in Analyze format), upload strip-masks that you create from these volumes, compare your masks against both sets of our manual masks, and return the results of these comparisons by e-mail. To utilize this Web service, please visit the INC Website, www.neurovia.umn.edu/incweb, after September 1, 2003.

If you wish to be informed when McStrip is released for download, leave your card (or name and e-mail address), or e-mail kelly@neurovia.umn.edu.

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